DESCRIBING EAST MALAYSIAN TADPOLE DIVERSITY: STATUS AND RECOMMENDATIONS FOR STANDARDS AND PROCEDURES ASSOCIATED WITH LARVAL AMPHIBIAN DESCRIPTION AND DOCUMENTATION

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ABSTRACT

Our ad hoc survey of 130 books and monographs showed that almost 70% did not present any descriptive information on larval anurans, and when larval stages were included the quality of documentation often tended to be poor. The larval (or developmental) stages of 51 species of east Malaysian frogs still remain unknown. Modern methods and techniques have changed the way we treat larvae taxonomically, and we recommend their adoption in tadpole research. Notably, DNA barcoding allows for unequivocal matching with adult frogs, and digital color photography provides documentation of tadpole features of unprecedented quality, partly replacing traditional drawings. Both techniques are considered essential for the study of tadpoles. Tadpole measurements have now reached a high level of standardization and can be performed quickly, accurately, and easily with digital microscopes. Nevertheless, line drawings and SEM may still be valuable techniques when certain details need to be demonstrated.

Key words: Biodiversity, tadpole, inventory, morphology, barcoding, field techniques herpetology, Amphibia, Anura.

INTRODUCTION

General

Declines in amphibian numbers are a global phenomenon but are most widespread and catastrophic in the tropics (Wake & Vredenburg 2008). There is thus an urgent need for studies on all amphibian life stages in the tropics, where entire assemblages are being lost before any acquisition of knowledge of their ecological roles. However, most ecological community analyses address adults and their ecological needs and interactions, whereas larval stages are rarely included (Inger *et al.* 1986, Inger & Voris 1993, Eterovick 2003, Eterovick & Barros 2003, Kopp & Eterovick 2006). In taxon-based books (e.g., Duellman & Trueb 1986, Wells 2007), larval stages usually receive much less attention than adults. This is rather surprising, considering that the biphasic life cycle of anurans imposes dramatically different selective regimes on the aquatic larval stage, the metamorphic stage, and the terrestrial post-metamorphic stage (Wilbur & Collins 1973, Wassersug 1975, 1997; Harris 1999, Hentschel 1999, Rose 2005). Most herpetologists would agree that the tadpole stage is just as crucial as the adult stage for the persistence of the species at a specific locality and for its success and distribution, and may play a decisive role in speciation processes, particularly in tropical assemblages. However, this is not yet reflected in the quantity and depth of contemporary research efforts to record larval diversity and to analyze the specific ecology of this unique life stage.

The recent accelerating increase in species descriptions (based on adults), and thus in the number of known anuran species (AmphibiaWeb 2010, Frost 2010), makes clear that a huge backlog of work, both taxonomic and ecological, is accumulating for studies on larval forms for future workers. Even basic knowledge, such as information on tadpole diets, is patchy and not well understood (Altig *et al.* 2007). We think that the lack of state-of-the-art tadpole descriptions, inventory catalogues, and reliable determination keys is a major impediment to scientific progress in biodiversity and ecology research on the larval amphibian semaphoront.

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In this paper, we give a brief overview on the status of tadpole descriptions as part of regional surveys and field guides in the literature. We report on our own project to record the tadpole diversity of East Malaysia. The main purpose of this paper is to 1) give a status report on the knowledge on the tadpole diversity in East Malaysia (Borneo); 2) communicate experiences and recommendation on standards and procedures that we have adopted, and 3) to argue that technological progress during the past ten years should change our standards in tadpole research. We think that some aspects of tadpole research are universal and we hope that our recommendations will facilitate the study of tadpole communities elsewhere, usually within tropical settings.

TADPOLE INVENTORIES

Tadpole

In order to briefly review the current attention that tadpoles receive in the herpetological literature, we surveyed a number of field guides, geographic herpetological surveys, and country faunal accounts (see Appendix 1). We included all sources that, to our knowledge, are designed to aid field and laboratory identification or are regional monographs and faunal revisions, published in the last 50 years. Although we do not claim that the list is comprehensive, the picture that emerges from evaluating these sources with respect to the coverage of tadpoles may well be indicative of the attention generally given to tadpoles in herpetological studies.

Among the 130 books and monographs examined, 90 (69.2%) did not present any descriptive information (morphological descriptions, drawings, or images) on tadpole life stages. Color images tend to be rare in published works: only 27 (20.7%) of the publications included color images of tadpoles, 15 (11.5%) for only a few species, and only 11 (8.5%) of the publications included color images of tadpoles for multiple species or all regional species known at the time. Among our sources, only four were exclusively devoted to larval forms (Inger 1985, Chou & Lin 1997, Anstis 2002, Beringhausen 2003). An additional work (Rödel 1998), while not on taxonomy, provides valuable data on tadpoles, including their identification.

When information on tadpoles was provided, we further categorized the quality and style of the illustrations (simple stylized sketches versus high quality line art). We did not try to be objective when assigning publications to one of these two categories, because drawings always are to some degree subjective interpretations of the object by the artist. Although the matching between the drawing and the original object, as well as the scientific precision, cannot be assessed without the object itself, the effort put into producing a quality drawing of a tadpole can usually be judged, and the value of a drawing for species identification is often evident. Examples of meticulously prepared drawings are in Anstis (2002) and Duellman (2001). However, only nine (6.9%) contained high quality line art and 33 (25.4%) contained only simple/stylized sketches.

The level of detail in tadpole textual description varies as much as in the illustrations. Tadpole descriptions cover a wide range, from brief descriptions of a few lines to highly detailed accounts with a wealth of morphological information. The usefulness of a given description for tadpole identification can be augmented if helpful illustrations and an identification key goes along with it. Short descriptions without supporting materials, as in the majority of the sources examined, will usually not suffice to allow reliable identifications and will be prone to ambiguity. An attempt to evaluate the documentation status for Bornean tadpoles has been published earlier (Das & Haas 2005: Tab. 1). For the tadpoles in Peninsular Malaysia, a summary was compiled by Leong (2002), who devised a preliminary scoring system to gauge the relative detail of documentation for each species.

The lack of our knowledge on the tadpole stages of frogs also becomes evident when considering tadpole identification keys. Among the sources examined, 34 (26.2%) provided some sort of identification key or other help for identification. However, some of the keys are to families or genera. Keys to the species level were rarely complete, as tadpoles of many species in the tropics remain unknown.

CURRENT KNOWLEDGE OF EAST MALAYSIAN TADPOLES

All amphibian species from Borneo (and indeed from the rest of the world) have been described largely, if not entirely, on the basis of adult specimens. Knowledge of tadpole descriptions has thus seriously lagged behind. At the last stock-taking, 89 of 160 species (less than 56%) then known from Borneo had known larval stages (Das & Haas 2005). Since this report appeared, larval descriptions of additional species occurring on the island have been published (Inger *et al.* 2006, Haas & Das 2008, Haas *et al.*

2009, Inger & Stuebing 2009, Leong & Teo 2009). New Bornean amphibian species have been described both with (e.g., Matsui *et al.* 2010) and without larval information (e.g., Dehling 2008, Dehling & Grafe 2008, Inger & Stuebing 2009). Data quality is yet another problem, as a significant proportion of larval descriptions lack voucher specimen information, are abbreviated, lack details expected in contemporary descriptions, or are not matched using DNA barcoding techniques. Furthermore, larval descriptions currently listed as available in Das & Haas (2005) are frequently derived from non-Bornean populations that under taxonomic revision may eventually prove to be non-conspecifics. Several familiar groups have been shown in recent years to represent taxonomically cryptic species (see for instance Inger *et al.* 2009).

At the time of this writing we identify the status of larvae of the following 51 species (taxonomically recognized for Borneo) as unknown (32% of all Bornean frogs):

Barbourula kalimantanensis, Ansonia echinata, A. fuliginea, A. latidisca, A. torrentis, Pedostibes everetti, Pelophryne api, P. guentheri, P. murudensis, P. linanitensis, P. rhopophilus, P. saravacensis, Pseudobufo subasper, Calluella brooksi, C. flava, C. smithi, Gastrophrynoides borneensis, Kalophrynus borneensis, K. eok, K. heterochirus, K. intermedius, K. nubicola, K. punctatus, K. subterrestris, Leptobrachella baluensis, L. brevicrus, L. parva, L. palmata, L. serasanae, Leptolalax dringi, L. hamidi, L. maurus, L. pictus, Borneophrys edwardinae, Ingerana baluensis, Limnonectes asperata, L. kenepaiensis, L. paramacrodon, L. rhachodus, Meristogeny jerboa, M. macrophthalmamus, Hylarana baramica, H. laterimaculata, H. picturata, H. megalonesa, Staurois latopalmatus, Rhacophorus everetti, R. fasciatus, R. gadingensis, R. rufipes, and *R. penanorum.*

However, our own efforts have yielded larval samples of the following taxa awaiting formal description in the future: *Calluella* sp., *Kalophrynus* sp., *Leptobrachella baluensis, L. brevicrus, Leptolalax dringi, Limnonectes paramacrodon, Meristogeny jerboa, Rhacophorus everetti, R. gadingensis, R. rufipes,* and *R. penanorum.* In Singapore, the discovery of tadpoles of *Hylarana laterimaculata* has been confirmed and their formal description is being prepared (T. M. Leong, pers. comm.).

RECOMMENDATIONS FOR TADPOLE DESCRIPTIONS

The lack of regional keys and field guides for tadpole identification is a hindrance for ecological and community studies on this important life stage of anurans. Considering the current backlog of taxonomic work in describing tadpoles around the world, it is important to make rapid progress in describing hitherto unknown tadpoles and in revising previous work containing abbreviated tadpole descriptions that were insufficient for reliable field and/or lab identification. Methods recruited for the taxonomic description of tadpoles should ideally be fast, simple, reliable, and should lead to a high quality of description. Although very similar tadpoles of cryptic species may exclude unequivocal identification by morphological methods in some cases, the paramount objective in tadpole descriptions should be to optimize reliable diagnostics as much as possible. Following the experience gained during our project on East Malaysian tadpoles, we would like to communicate some recommendations in this respect.

Line drawings

The current compilation (Appendix 1), and a previously published survey (Das & Haas 2005), show that many tadpole descriptions were in fact published without any illustrative figure of the tadpole concerned. Among published tadpole descriptions with figures, line drawings have been a frequently chosen option for more than a hundred years up to the present (Inger *et al.* 2006). We believe that the historic predominance of line drawings in illustrating tadpoles was mainly due to the ease of production and lack of alternative technologies. Line drawings had clear advantages: 1) easy to make; 2) low cost in producing the drawing and producing the print; 3) clarity with which certain structures can be shown (e.g, mouthparts); 4) relatively simple to reproduce and scale at good quality (via paper photocopy); 5) ease of grouping drawings on plates for interspecific comparisons.

However, these advantages of line drawings are perhaps outweighed by several disadvantages: 1) loss of color information; 2) loss of pigmentation information; 3) researchers may decide to hand the drawing process to an artist who is not familiar with the taxonomically relevant character states (a potential source of additional errors of detail); 4) accuracy of drawings depends on the skill of the artist and the process employed; 5) one and the same individual tadpole drawn by two different artists can look quite different (i.e., non-repeatable); 6) drawings made from preserved specimens may have altered body shapes (bending of axial skeleton, shrinkage of artifact caused by preservatives).

The lack of illustrations and, if present, the predominance of line drawings in the literature with their specific disadvantages, limit the immediate use of published information. In other words, an ecologist planning a community-level study on tadpoles in the tropics will hardly be able to compile enough information from the literature to be able to reliably identify living specimens in a given field situation (not to mention unknown species). The use of line drawings for the illustration of tadpoles was justified in the early days because it was for long the best technique and alternatives were not available. At the end of the 20th century, color analog photography became feasible (see Anstis 2002), but it was expensive and needed training in creating and manipulating images. Furthermore, most journals were unable or reluctant to print color images. The predominance of line drawings is thus mostly a phenomenon of community inertia. Novices in the field tend to do things the way their predecessors did. Although line drawings are still useful for some purposes (clear depiction of the tadpole mouthparts, interspecific comparisons), all other purposes of illustration are, in our opinion, fulfilled better by contemporary photographic techniques.

Tadpole photography

There are excellent examples of tadpole inventories and taxonomic descriptions that demonstrated the usefulness of tadpole color photography (Chou & Lin 1997, Leong & Chou 1999, Anstis 2002, Leong 2004). During the past 10 years, the advent and rapid progress of digital photography has profoundly changed our approach to image acquisition and processing. For the first time catalogues of vast numbers of high quality images can be collected for biodiversity projects at relatively low cost (no film material or complicated post-production work needed). Various software packages (Adobe® Lightroom, Apple® Aperture) allow the handling and meta-data annotation of image catalogues containing several tens of thousands of images, allowing for rapid comparisons of tadpoles among various regions or study sites.

The resolution and quality of images has steadily increased and any camera with a 10 megapixel (MP) sensor chip will satisfy a biologist's needs for image quality in most situations. Image quality can be assessed and adjusted immediately. Along with digital cameras, flash control systems have evolved substantially. All major camera manufacturers offer wireless-controlled flash systems, making multiple flash setups easy to handle in field situations. As most measurements and data exchanges between flash and camera are automatic in today's camera systems, images can be evaluated immediately after exposure on the camera screen. In general, little intervention by the photographer is necessary and the technique is simple and reliable in most field situations.

For tadpole photography we use customized mini-aquaria of 20 x 10 x 4 cm (width x height x depth) with a glass thickness of 4 mm. The aquarium usually contains 2 cm of sand and some rocks to position the tadpole. We anesthetize tadpoles in a separate plastic container with a weak solution of chloretone (approx. 0,1% 1,1,1-trichloro-2-methyl-2-propanol) and transfer specimens to the photo aquarium once anesthetized. However, others (Julian Glos, pers. comm.) prefer adding MS 222 (tricaine methanesulfonate) directly into the aquarium. Mid-column feeders, such as microhylid tadpoles, may assume unnatural postures when anesthetized. Microhylid tadpoles and similar feeding specialists need to be photographed without anaesthesia, which offers challenges in terms of obtaining images from all required perspectives. The eggs of directly developing species are difficult to find in the field. Some eggs of *Philautus* species have been discovered in pitcher plant pitchers (see Malkmus *et al.* 2002). Such clutches are best photographed *in situ.* However, if developmental stages are to be recorded, they must be transported in a plastic box to the lab while maintaining appropriate light, moisture, and temperature conditions.

The preferred lens for tadpole photography is a 100 or 105 mm macro lens. It allows sufficient distance between the front end of the lens and the aquarium to position light modifiers. Furthermore, its telephoto angle of view approaches a parallel projection of view better than a lens with shorter focal length. This is advantageous with respect to the refraction effects (distortion) in the aquarium (air-glass-water transition), particularly towards the periphery of the image. Excellent lighting can be achieved by placing the main flash unit (wirelessly controlled) on top of the aquarium and positioning a second flash with reduced power output to the left of the camera to fill in shadows from an angle. Tadpoles are photographed facing to the left in order to show the position of the spiraculum on the left side of the body in most species. By choosing different background colors (Anstis 2002), it can be ensured that the outline of the tadpole tail fin is clearly visible on the images (Fig. 1). Additional extension tubes allow for magnifications well beyond 1:1 and allow the documentation of finer patterns in pigmentation or details of mouthparts. Such images were much more difficult to achieve with analog film cameras.

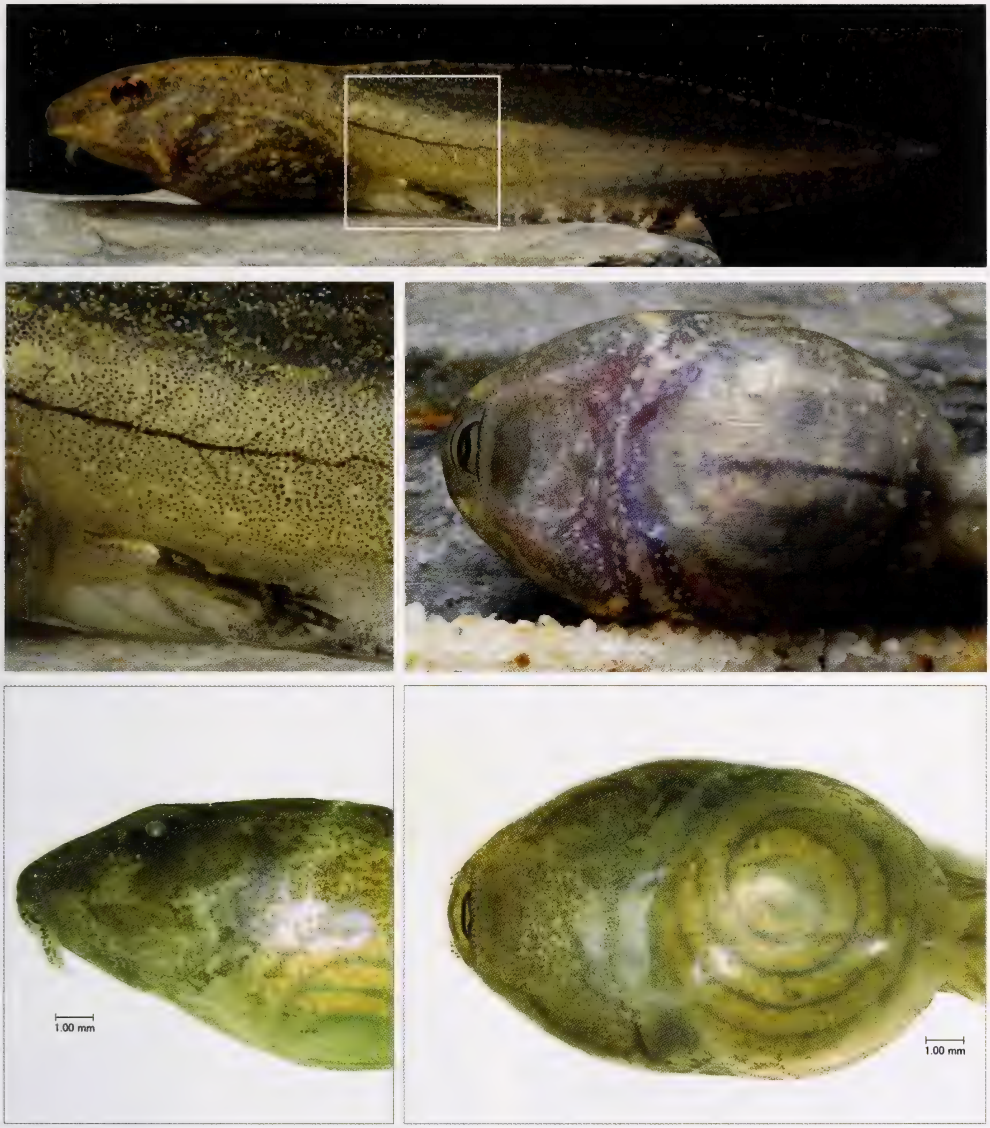

FIG. 1. Lateral view of *Hylarana nicobariensis* (top) from Sabah, digital photograph of an anaesthetised specimen set up in a mini-aquarium (20 x 10 x 4 cm, WHD) (Nikon D80 [10 megapixel sensor], Sigma Macro 105 mm; ISO 250, f/16, wirelessly controlled SB 600 flash from top). In most species a black background is suitable to show the tail fin contour. A magnification (middle left) of the cropped part of the top image (white square) shows the level of detail and limits of resolution with the camera/lens combination used. The ventral perspective of the living tadpole (middle right, same specimen) gives valuable color and pigmentation details. The lower left and right images show the same individual as above after formalin preservation. Backgrounds have been cropped. The color information that can be gained from preserved specimens is largely reduced; compare ventral views and iris in life and in preservation. For scale see bottom images; generated with a Keyence VHX-500 digital microscope.

Further advances in tadpole research can be achieved by applying high speed videography. High speed video recording is an essential tool to record the rapid raking movements of tadpole jaws and keratodonts during feeding (Venesky *et al.* 2010) or the details of various swimming behaviours (Roberts *et al.* 2000). Rapid progress in technology will likely facilitate field work with high speed technology, as the technology gets more affordable and the sensors more sensitive. We sucessfully used a consumer-grade Casio Exilim EX-FH20 digital camera for filming the grazing behavior of *Meristogenys jerboa* in the above-mentioned tank at 400 frames per second, under field conditions.

In summary, properly lit, standardized lateral and ventral digital photographs of tadpoles capture the body shape, proportions, and pigmentation details in far superior quality than any line drawing could accomplish (Fig 1). During our inventory of East Malaysian tadpoles, systematically collected digital color images of tadpoles have proven to be an indispensable tool for their identification. Tadpole photography with modern digital camera equipment can be considered a technological paradigm shift, that 1) makes taking high quality images much simpler than in analog photography; 2) allows the taking of large numbers of images for documentation of variation; 3) provides good color rendition; 4) is superior to drawings in maintaining correct body proportions and showing details; 5) captures valuable details in living specimens that vanish in preservation (silver and golden iridocytes). At present, a number of journals print color images in high quality from digital files.

Measurements

A variety of external characters are accessible to measurement in tadpoles. Although various authors may use slightly different measurements, lists of measurable variables have been proposed (e.g., Altig & McDiarmid 1999; Fig. 2). The intraspecific ontoge-

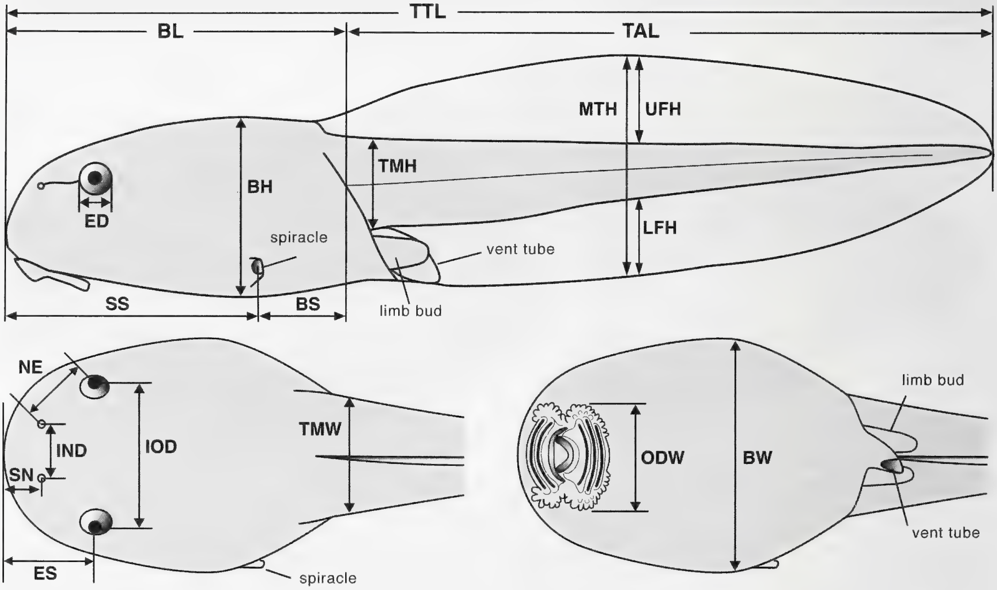

FIG. 2. Proposed standard tadpole body measurements developed from definitions by Altig & McDiarmid (1999). BH, body height; BL, body length from snout to the point where the axis of the tail myotomes meets the body wall; BS, body end to center of spiracle; BW, maximum body width; ED, eye diameter; ES, eye-snout distance; IND, internarial distance (center to center); IOD, interorbital distance; LFH, lower fin height (at MTH); MTH, maximum tail height; NE, distance from center of naris to center of eye; ODW, oral disk width; SN, distance of naris (center) from snout; SS, distance of snout to center of spiracle; TAL, tail length (=TL-BL); TMH, tail muscle height at body-tail junction, where ventral line of musculature meets trunk contour; TMW, tail muscle width at the same level as TMW; TTL, total length; UFH, upper fin height.

netic stability of commonly used measurements has recently been assessed and pertinent literature discussed (Grosjean 2005). Grosjean (2005) showed that a number of external and internal features remain stable during ontogeny, whereas others (such as tail fin height) may vary as a response to external factors. He recommended taking tadpoles of stages 32–40 (Gosner 1960) for tadpole descriptions, because in this phase many taxonomically relevant character states are stable.

Taking measurements has become much more efficient with the advent of digital microscopy. Using camera lucida devices, or measuring eyepieces, has been replaced by calibrated digital imaging. Modern digital microscopes (e.g., Keyence VHX Series) not only allow rapid measurements from calibrated digital images but also offer greater depth of field than standard stereomicroscopes. Digital images thus taken can further be used as backdrops for drawings of any kind.

SEM

After the scanning electron microscope had been devised (von Ardenne 1938) it rapidly became a popular tool in biological sciences in the second half of the 20th century. SEM has been used widely in tadpole research (e.g., Wassersug 1976,1980; Wassersug & Rosenberg 1979; Viertel 1982; Inger 1985, Wassersug & Heyer 1988; Das 1994; Hall & Larsen 1998). SEM was used in tadpole descriptions primarily to show the mouthparts and the internal oral and buccal soft tissues (e.g., Grosjean 2005, Haas & Das 2008). However, if no SEM is available, major qualitative tadpole characters (mouthpart papillation, buccal floor/roof papillation) can be recorded by alternative methods, such as methylene blue (e.g., Anstis 2002, Aguayo *et al.* 2009) or crystal violet (Altig 2007) staining and subsequent capture of images with a digitally equipped microscope. These stains give more contrast to otherwise translucent papilla. SEM will render keratodonts in a 3-dimensional fashion, though keratodonts can be put on microscopic slides and studied by light microscopy as well (Aguayo *et al.* 2009). Thus the unavailability of SEM technology is no hindrance in describing tadpoles at high levels of detail.

DNA barcoding

DNA barcoding uses mitochondrial gene sequences that can be amplified with universal primers in order to facilitate species identification and description, reveal cryptic species, or link highly dimorphic males and females. Furthermore, in biphasic organisms, such as arthropods and amphibians, barcoding techniques are an efficient tool to link tadpoles to their adult semaphoronts. Although it is still debated whether CO1 or 16S is the more efficient gene in amphibian barcoding (Vences *et al.* 2005a, Vences *et al.* 2005b, Smith *et al.* 2008), it is unquestioned that barcoding techniques are a major advance in tadpole research (Inger *et al.* 2006, Haas & Das 2008, Hendrix *et al.* 2008, Haas *et al.* 2009, Randrianiaina *et al.* 2009; see application in Gawor *et al.* 2009). Some researchers have tried to identify tadpoles by raising them through metamorphosis. This approach has been successful with species that develop unique color patterns on their thighs or dorsum at pre- or mid-metamorphic stages, such as *Polypedates otilophus* or *Hylarana luctuosa* among Bornean species. In less conspicuous species, metamorphs may be indistinct from unrelated species that occur in syntopy (e.g., *Polypedates colletti*; pers. obs.) or even highly divergent in their color pattern from adults (*Rhacophorus nigropalmatus*; Ready 2009) making assignments ambiguous or erroneous. Barcoding techniques could clarify previously ambiguous tadpole assignments (Haas & Das 2008, Haas *et al.* 2009). DNA barcoding is 1) easy to perform; 2) relatively affordable; 3) can be done completely by a contractor if a molecular lab is not available; 4) is far more reliable in linking tadpoles to adults than traditional techniques; and 5) allows us to identify any developmental stage from egg to adult.

Data richness and dissemination

The highly variable depth and quality of available tadpole descriptions (Das & Haas 2005) impose limitations on tadpole research. However, some published works point the way towards a standard in depth of treatment (e.g., Inger 1985, Chou & Lin 1997, Leong & Chou 1999, Duellman 2001, Anstis 2002, Leong 2004) for the tadpole faunas of southeast Australia, Taiwan, Middle America, and the Malay Peninsula, respectively. Peer-reviewed journal articles are the preferred method of publishing taxonomic information. This ensures quality, but taxonomic information becomes only slowly available. Dissemination of taxonomic information via internet portals cannot be an alternative, but a supplementary way to provide taxonomic resources. Data from our own project are integrated in Haas & Das (2010). Web publication of supplementary information such as imagery and short descriptions is 1) fast; 2) easily accessible from all parts of the world; and 3) can summarize regional faunal information otherwise too scattered or cryptic to access. Several web portals have been devised for amphibians (e.g., AmphibiaWeb 2010, Frost 2010, Norhayati *et al.* 2010), but to the best of our knowledge only two (Altig *et al.* 1998, Haas & Das 2010) cover larval forms with images for quick reference.

CONCLUSIONS

Recent technological developments provide tools that facilitate the description of tadpoles. Contemporary procedures, such as digital photography and digital microscopy, are not only more efficient and easier to apply than older technologies, but offer a high level of precision and data quality, contributing to the goal of reliable tadpole diagnostics. Efforts to catalogue tadpole communities, particularly in the species-rich tropics, should adopt the new techniques rather than uncritically following outdated schemes of tadpole descriptions. We conclude: 1) Digital photography of living specimens and subsequent color prints in publications are indispensable for tadpole descriptions. Good photographs give a great amount of information and can replace traditional drawings to a large extent. 2) Drawings should be used when they can deliver clarity better than other methods (mouthparts, contour line, interspecific comparisons). 3) DNA barcoding has become affordable and easy to handle. Tadpole identities should initially be confirmed by DNA matching to adults, until reliable morphological diagnostics have been established. 4) Standard morphological features and morphometric traits must be recorded (Grosjean 2005, Altig 2007). Digital microscopes facilitate the taking of measurements. 5) Soft tissue tadpole characters can be examined with staining techniques if an SEM is not accessible. 6) Tadpole descriptions should be published in peer-reviewed journal articles. However, internet portals are a fast and universally accessible, supplementary source to disseminate descriptions, keys, image catalogues, and regional inventories.

ACKNOWLEDGMENTS

We thank the Sarawak Forest Department, in particular Datuk Cheong Ek Choon, Director, Haji Ali bin Yusop, Bolhan Budeng, Azahari bin Omar, and Mohd. Shabudin Sabki for issuing permits (NPW.907.4–36, NPW.907.4.2(IV)–3, Park Permit 3/2009) and export permits (07094–97), and Sabah Parks, especially Jamili Nais, Director of Research, for issuing collecting permit (TS/PTD/5/4 Jld. 25 (41). We are grateful to Aaron Bauer for references. Our research on the tadpoles of Borneo was supported by our respective institutions, Biozentrum Grindel and Zoologisches Museum Hamburg, and the Institute of Biodiversity and Environmental Conservation, Universiti Malaysia Sarawak. The Economic Planning Unit, The Prime Minister's Department, Malaysia, and especially Munirah Abd. Manan, issued permission to conduct research in Malaysia to A. Haas. This research was supported by the Volkswagen Foundation, Germany, Grant I/79 405. We also thank Stefan T. Hertwig and The Natural History Museum, Berne, for additional support stemming from parallel joint projects. The work and contributions of friends and students, who were involved over the years, is gratefully acknowledged: Jeet Sukumaran, Kelvin Boon Hee, André Jankowski, Jörg Hofmann, Johanna Wolter, Maximilian Dehling, Torben Riehl, Sebastian Marwitz, Daniela Haarmeyer, Melitta Wunderskirchner, Cindy Hefenbrock, Sandra James Tinggom, Castro Micheal, Lily Sir, Mohd. Iqbal Makmor, Khairul Anuar bin Omar, Yolande Direp ak Michael Direp, Hairi bin Hedeir, Siti Shuhada bt Mustaffa, Pui Min Yong, Mona Octavia Sulai. We thank the organizers of the Tropical Biology meeting in Bonn for their hospitality and the opportunity to present this work, and finally, Wolfgang Böhme and Tzi Ming Leong for comments on the manuscript.

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APPENDIX 1. Compilation of field guides, geographic herpetological surveys, and country faunal accounts that have been in used for the past 50 years in the identification of amphibians. Assessment of contents with respect to anuran amphibian larval stages: 0, absent; 1, present; S, short description; L, long detailed description (including measurements).

References	Country/Geographical Region	Morphology data	Color photos/ paintings	High quality line art	Simple/ stylized sketches	Identification keys	Description detail: Absent (0)/ Short (S)/ Long (L)
Ahmed *et al.* (2004)	Endau Rompin, Peninsular Malaysia	0	0	0	0	0	0
Ahmed *et al.* (2005)	Ulu Muda, Peninsular Malaysia	0	0	0	0	0	0
Ahmed *et al.* (2009)	North-east India	0	0	0	0	0	0
Alcala (1986)	Philippines	0	0	0	0	0	S
Alcala & Brown (1998)	Philippines	0	0	0	0	0	0
Almonacid *et al.* (2005)	South America	0	0	0	few spp. of *Atelopus*	0	0
Anstis (2002)	South-east Australia	1	1	1	0	1	L
Auerbach (1987)	Botswana	0	0	0	0	0	0
Baier *et al.* (2009)	Cyprus	0	1 sp,	0	0	0	0
Baloutchi & Kami (1995)	Iran	0	0	0	0	0	0
Baran (2005)	Turkey	0	0	0	0	0	0
Barker *et al.* (1995)	Australia	1	0	0	0	0	S
Behler & King (1979)	North America	0	0	0	0	0	0
Beringhausen (2003)	Germany	1	1	0	0	1	S
Berry (1975)	Peninsular Malaysia	0	0	0	0	0	0
Beshkov & Nanev (2006)	Bulgaria	0	0	0	0	0	0
Branch (2005)	East Africa	0	0	0	0	0	0
Brennan & Holycross (2006)	Arizona, USA	0	0	0	0	0	0
Carruthers (2001)	Southern Africa	1	few spp.	0	0	0	0
Chan-ard (2003)	Thailand	0	0	0	few spp.	0	0
Chanda (1994)	North-east India	0	0	0	0	0	0
Chanda (2002)	India	0	0	0	0	0	0
Channing (2001)	Central and Southern Africa	1	0	1	0	1	S
Channing & Howell (2005)	East Africa	1	0	1	0	1	S
Chou & Lin (1997)	Taiwan	1	1	1	0	1	L
Christie (1997)	Prince Edward County, Ontario, Canada	0	0	0	0	0	0
Cogalniceanu *et al.* (2000)	Romania	0	0	0	1	0	S
Cogger (1994)	Australia	0	0	0	0	0	0
Conant & Collins (1998)	Eastern/Central USA	0	0	0	1	0	S

APPENDIX 1. Continued.

References	Country/Geographical Region	Morphology data	Color photos/ paintings	High quality line art	Simple/ stylized sketches	Identification keys	Description detail: Absent (0)/ Short (S)/ Long (L)
Corkran & Thoms (2006)	Oregon and Washington, U.S.A. and British Columbia, Canada	0	1	0	0	1	S
Daniel (2002)	India	0	0	0	0	0	S
Daniels (2005)	Peninsular India	0	0	0	0	0	0
Das (2007)	Brunei Darussalam	0	0	0	0	0	0
de Silva (2009)	Sri Lanka	0	0	0	0	0	0
Desroches & Rodrigues (2004)	Quebec, Canada	0	0	0	0	1	S
Disi (2002)	Jordan	0	0	0	0	1	0
Disi *et al.* (2001)	Jordan	0	0	0	0	1	S
Duellman (2001)	Middle America	1	0	1	0	diagnostic table	L
Duguet & Melki (2003)	France, Belgium and Luxembourg	1	1	0	0	1	S
du Preez & Carruthers (2009)	Southern Africa	0	1	0	few spp.	1	0
Dutta & Manamendra-Arachchi (1996)	Sri Lanka	0	0	0	0	0	0
Engelmann *et al.* (1985)	Europe	0	0	0	1	1	S
Fei & Ye (2001)	Sichuan, China	0	few spp.	0	few spp.	1	S
Fei *et al.* (1999)	China	0	few spp.	0	0	1	S
Fei *et al.* (2005)	China	0	0	0	1	1	0
Fei *et al.* (2009a)	China	0	0	0	1	0	S
Fei *et al.* (2009b)	China	0	0	0	1	0	S
Fisher *et al.* (2007)	Canada	0	0	0	0	0	0
Franzen *et al.* (2008)	South-western Turkey	0	1	0	0	0	S
Gallardo (1987)	Argentina	1	0	0	0	0	S
Geniez *et al.* (2004)	Western Sahara	0	0	0	0	0	0
Gibbs *et al.* (2007)	New York, USA	1	0	0	0	0	S
Gilhen (1984)	Nova Scotia, Canada	0	0	0	0	0	S (measurements)
Glandt (2010)	Europe	0	0	0	0	0	S (measurements)
Glaw & Vences (2007)	Madagascar	0	0	0	0	0	0
Goris & Maeda (2004)	Japan	1	0	0	0	0	S
Grismer (2002)	Baja California, Mexico	1	0	0	0	0	S
Günther (1996)	Germany	1	0	1	0	1	L
Guyer & Donnelly (2005)	La Selva, Costa Rica	0	0	0	0	0	0
Henkel & Schmidt (2000)	Madagascar, Mascarene, Seychelles and the Comoro archipelago	1	0	0	0	0	S

APPENDIX 1. Continued.

References	Country/Geographical Region	Morphology data	Color photos/ paintings	High quality line art	Simple/ stylized sketches	Identification keys	Description detail: Absent (0)/ Short (S)/ Long (L)
Inger (1966)	Borneo	1	0	0	1	1	L
Inger (1985)	Borneo	1	0	0	0	1	L
Inger & Stuebing (1989)	Sabah, Malaysia	0	0	0	0	0	S
Inger & Stuebing (2005)	Borneo	0	0	0	0	0	S
Iskandar (1998)	Java and Bali, Indonesia	1	0	0	1	1	S
Jaafar *et al.* (2008)	Pulau Pinang, Peninsular Malaysia	0	0	0	0	0	0
Jacob *et al.* (2007)	Wallonie (French-speaking Belgium)	0	1	0	0	0	S
Jewel (2008)	New Zealand	0	few spp.	0	0	0	S
Jongbloed & Brown (2000)	United Arab Emirates	0	0	0	0	0	0
Jovanovic *et al.* (2007)	Madagascar	0	0	0	0	0	0
Kabir *et al.* (2009)	Bangladesh	1	one sp. (Clinotarsus alticola)	0	0	0	S
Karsen *et al.* (1998)	Hong Kong	0	0	0	0	0	S
Khan (2006)	Pakistan	1	0	0	0	1	S
Kubicki (2007)	Costa Rica	1	few spp.	0	0	0	S
Kuzmin & Maslova (2005)	Russian Far East	1	0	0	1	0	L
Le Berre (1989)	North Africa	0	0	0	0	1	S
Lee (2000)	Mexico, Guatemala, Belize	1	0	0	1	0	S
Lehr (2002)	Peru	0	0	0	0	0	0
Leviton *et al.* (1992)	Middle East	0	0	0	1	1	0
Lim & Lim (2002)	Singapore	0	few spp.	0	1	0	S
MacCulloch (2002)	Ontario, Canada	0	1	0	0	0	S
Malkmus (2004)	Portugal, Madeira and the Azores Archipelago	0	1	0	0	0	0
Malkmus *et al.* (2002)	Mount Kinabalu, Malaysia	1	few spp.	few spp.	few spp.	genera	S
Manthey & Grossmann (1997)	South-east Asia	1	few spp.	0	1	family	S
Mathew & Sen (2010)	North-east India	0	0	0	0	0	0
Matsuda *et al.* (2006)	British Columbia, Canada	0	0	0	0	0	S
Matz & Weber (1983)	Europe	0	0	0	0	0	S
McCranie & Wilson (2002)	Honduras	1	0	0	few spp.	1	S/L
McKay (2006)	Bali, Indonesia	1	0	0	0	1	S
Menzies (1976)	New Guinea	0	0	0	0	0	0

APPENDIX 1. Continued.

References	Country/Geographical Region	Morphology data	Color photos/ paintings	High quality line art	Simple/ stylized sketches	Identification keys	Description detail: Absent (0)/ Short (S)/ Long (L)
Minton (1966)	Pakistan	1	0	0	0	0	S
Murphy (1997)	Trinidad & Tobago	0	0	0	0	0	0
Necas *et al.* (1997)	Czech Republic	0	few spp.	0	0	0	S
Nguyen *et al.* (2009)	Vietnam	0	0	0	0	0	0
Nöllert & Nöllert (1992)	Europe	1	0	1	0	1	detailed (as part of key)
Nutphand (2001)	Thailand	0	0	0	few spp.	0	0
Passmore & Carruthers (1995)	South Africa	0	0	0	0	0	0
Pickersgill (2007)	Southern and eastern Africa	1	0	0	1	0	L
Pikacha *et al.* (2008)	Solomon Islands	0	0	0	0	0	0
Poynton (1964)	Southern Africa	0	0	0	0	0	0
Preston (1982)	Manitoba, Canada	0	0	0	1 sp. (Lithobates sylvatica)	1	S
Razzetti & Msuya (2002)	Tanzania	0	0	0	0	0	0
Renjifo (2000)	Colombia	0	0	0	0	0	0
Renjifo & Lundberg (1999)	Urra, Colombia	0	0	0	0	0	0
Rivero (1972)	Venezuela	0	0	0	0	0	0
Rödel (1998)	Ivory Coast	0	few spp.	0	1	0	0
Rödel (2000)	Ivory Coast	1	0	1	1	0	L
Russell & Bauer (2000)	Alberta, Canada	0	0	0	0	1	S
Saleh (1997)	Egypt	0	0	0	0	0	0
Salvador & Paris (2001)	Spain	0	0	0	1	1	S
Savage (2002)	Costa Rica	1	0	0	1	1	S
Schiøtz (1999)	Africa	1	0	0	few spp.	0	S
Schleich & Kästle (2002)	Nepal	1	0	0	few spp.	genus	0
Schleich *et al.* (1996)	North Africa	1	0	0	1	1	S
Shim (2003)	Korea	0	few spp.	0	few spp.	0	0
Shrestha (2001)	Nepal	0	0	0	0	0	S
Stewart (1967)	Malawi	0	0	0	0	0	S for a few spp.
Taylor (1962)	Thailand	0	0	0	0	0	0
Terbish *et al.* (2006)	Mongolia	0	0	0	0	0	0
Thy & Holden (2008)	Cambodia	0	0	0	0	0	0
Trapp (2007)	Greece (mainland)	0	0	0	0	0	0
Tyler *et al.* (2000)	Western Australia	0	0	0	0	0	0

APPENDIX 1. Continued.

References	Country/Geographical Region	Morphology data	Color photos/ paintings	High quality line art	Simple/ stylized sketches	Identification keys	Description detail: Absent (0)/ Short (S)/ Long (L)
Valakos *et al.* (2008)	Greece	0	0	0	0	1	0
Wager (1986)	South Africa	1	few spp.	0	1	0	S
Wu *et al.* (1987)	Guizhou, China	0	0	0	some b&w photos	0	S
Yang (1991)	Yunnan, China	1	0	0	0	0	S
Yang (1998)	Taiwan	1	few spp,	0	few spp.	0	0
Yang & Rao (2008)	Yunnan, China	0	0	0	0	0	0
Zhao & Adler (1993)	China	0	0	0	0	0	0
Ziegler (2002)	Vietnam	1	1	0	0	0	0